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**TURBOJET EMISSIONS, HYDROGEN  
VERSUS JP**

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## ABSTRACT

Preliminary data from an experimental combustor show that the  $\text{NO}_x$  emission index,  $\text{g}(\text{NO}_2)/\text{kg}$  fuel, is about three times greater for hydrogen than for JP at simulated cruise conditions. However, if these results are applied to aircraft designed for a given mission, hydrogen's higher heating value enables the aircraft to have a lower gross weight and a lower fuel flow rate so that the  $\text{NO}_x$  emission rate,  $\text{kg}(\text{NO}_2)/\text{hr}$  may be reduced about 30 percent compared to JP. Theoretical kinetics calculations indicate that combustors may be designed for hydrogen that could further decrease  $\text{NO}_x$  emissions by taking advantage of hydrogen's wide flammable limits and high burning velocity.

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## TURBOJET EMISSIONS, HYDROGEN VERSUS JP

by Jack Grobman, Carl Norgren, and David Anderson

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## SUMMARY

The purpose of this report is to compare predicted nitrogen oxide emissions, characteristic of future subsonic and supersonic commercial jet aircraft, using either hydrogen or kerosene (JP) fuel. The use of hydrogen fuel would obviously eliminate the carbon monoxide, total hydrocarbons, and smoke contributed by aircraft using kerosene. Attention is therefore focused on the relative quantities of nitrogen oxides ( $\text{NO}_x$ ) generated by using either fuel. Considerably more potential exists for minimizing nitrogen oxide emissions with hydrogen than with kerosene because of its wider flammable limits and higher burning velocity, and because it may easily be introduced into the combustor as a gaseous fuel.

The results of analytical chemical kinetics calculations are discussed to indicate the ideal ultimate reductions in nitrogen oxide emissions that might be predicted using either hydrogen or kerosene fuel. Emission data are also compared for hydrogen, ASTM A-1, and propane fuel tested in an experimental combustor segment at simulated engine cruise conditions. The experimental combustor that was used to obtain a comparison of hydrogen and hydrocarbon emissions was not specifically designed to minimize emissions; nevertheless, these data do indicate the trends and sensitivities of nitrogen oxide emissions with combustor operating conditions. These preliminary experimental data were used to predict nitrogen oxide emissions during cruise for both an advanced subsonic and an advanced supersonic commercial jet aircraft. The  $\text{NO}_x$  emission index,  $\text{g}(\text{NO}_2)/\text{kg fuel}$ , is shown to be about three times greater for hydrogen than for JP; however, if these results are applied to aircraft designed for a given mission, hydrogen's higher heating value enables the aircraft to have a lower gross weight and a lower fuel flow rate so that the  $\text{NO}_x$  emission rate,  $\text{kg}(\text{NO}_2)/\text{hr}$  may be reduced about 30 percent compared to JP. These results should not be interpreted as being optimum because the combustor used was not optimized for minimum emissions and because the analytical chemical kinetics calculations indicate that much greater reductions are theoretically possible than were observed experimentally.

Extensive research was performed in the mid-fifties at NASA-Lewis to adapt the use of hydrogen fuel to gas turbine engines for high altitude aircraft. One of the more promising combustor concepts for burning hydrogen evolved at that time was the "swirl-can" combustor. Considerable research is currently being performed by NASA-Lewis to reduce nitrogen oxide emissions in advanced combustors using kerosene fuel. The "swirl-can" combustor has been one of the more promising concepts being examined to achieve this task. Emission data have not yet been obtained for hydrogen in a "swirl-can" combustor; however either the "swirl-can" combustor or some other type of premixed combustor should have considerable potential for minimizing nitrogen oxide emissions in jet aircraft using hydrogen.

## INTRODUCTION

The purpose of this report is to predict and compare exhaust pollutant emissions, characteristic of future subsonic and supersonic commercial aircraft, using either hydrogen or kerosene (JP) fuel. The potential of liquid hydrogen as a jet fuel for high altitude aircraft was discussed in detail in reference (1). Extensive research was performed in the mid-fifties at NASA-Lewis Research Center to adapt the use of hydrogen fuel to gas turbine engines for high altitude aircraft (ref. 2). Considerable experience was gained with hydrogen both in the modification of existing combustors designed for using kerosene fuel and in the generation of combustor technology that utilized hydrogen's unique combustion properties (ref. 2-7).

Jet aircraft may contribute to either urban pollution by influencing air quality in the vicinity of airports or to global pollution by influencing the composition of constituents in the stratosphere. Using hydrogen avoids the low power - engine idle emissions problem by eliminating carbon monoxide and hydrocarbons as exhaust products. In addition, the problem of exhaust smoke during the take-off mode is completely eliminated with the use of hydrogen.

Attention is therefore focused on the relative quantities of nitrogen oxides ( $\text{NO}_x$ ) generated by using either fuel. The rate of formation of nitrogen oxides in gas turbine combustors is much slower than the fuel combustion reactions, and the amount formed varies exponentially with flame temperature and nearly linearly with reaction zone dwell time (ref. 8). The major approach for reducing nitrogen oxide emissions is

therefore to reduce reaction zone temperature and dwell time to the minimum values that allow the combustion reactions to be completed. Lower reaction zone temperatures may be attained by operating with lower primary zone fuel-air ratios and by uniformly mixing the fuel and air prior to combustion. Reduced reaction zone dwell time may be attained by using as short a primary zone as possible and by quenching the reaction with secondary air as quickly as possible.

The relative combustion properties of hydrogen and kerosene are examined herein to compare their potential for minimizing nitrogen oxide emissions. The results of analytical chemical kinetics calculations are discussed to indicate the ideal ultimate reductions in nitrogen oxide emissions that might be predicted using either hydrogen or kerosene fuel. Emission data are also compared for hydrogen, ASTM A-1, and propane fuel tested in an experimental combustor segment at simulated engine cruise conditions. The experimental emission data for hydrogen and ASTM A-1 are used to make predictions for the nitrogen oxide emissions that might be expected during cruise from advanced subsonic and supersonic commercial jet aircraft. In addition, the application of previous combustor experience gained with hydrogen to the design of low emission combustors is discussed.

## COMBUSTION PROPERTIES

The combustion properties of hydrogen are discussed in detail in references (2 and 9). Hydrogen has a heating value that is approximately 2.75 times greater than the heating value for JP fuel. The stoichiometric fuel-air ratios for hydrogen and JP fuel are 0.029 and 0.067, respectively. The heat sink capacity of liquid hydrogen would be used for cooling hot components in the engine (ref. 10); therefore, hydrogen could be introduced into the combustor as a gaseous fuel. Two properties of any fuel that characterize its potential performance in a gas turbine combustor are (1) flammability range and (2) burning velocity.

### Flammability Range

Hydrogen has a much wider flammability range than JP. At the lean limit, hydrogen has an equivalence ratio of about 0.1 to 0.2 compared to a value of about 0.5 for kerosene type fuels. Equivalence ratio,  $\phi$ , is defined as the quotient of the fuel-air ratio of a given mixture divided by the stoichiometric fuel-air ratio. The rich limit for hydrogen occurs at

an equivalence ratio of about 7 compared to a value of about 4 for kerosene.

Pressure (above 1 atmosphere) does not have a significant effect on the flammable limits; however, increasing the initial mixture temperature widens the flammability range. The lowering of the lean limit and raising of the rich limit are linear with increasing temperature. Regardless of the initial temperature, the flame temperature for hydrogen burning in air is 1000 to 1100 K at the lean limit and 1200 to 1300 K at the rich limit (ref. 9). The flame temperature for kerosene would be expected to be about 1900 K at the lean limit and 1200 K at the rich limit.

From the viewpoint of combustor performance, a wide flammability range enhances combustion stability over a wide range of required engine operating conditions that include a large span in fuel flowrate. In the past, combustor engineers have designed gas turbine combustors with the primary zone operating near an equivalence ratio of unity at cruise or take-off conditions. The formation of nitrogen oxides may be minimized by designing the primary zone (reaction zone) to operate at as low a flame temperature as possible. This may be accomplished by burning near the lean flammable limit within the primary zone. Since hydrogen has a wider flammable range than JP fuel, it has a greater potential for minimizing the formation of nitrogen oxides. As indicated previously, at their lean limit, the flame temperature for hydrogen is about 1000 to 1100 K and for JP is about 1900 K. Furthermore, since hydrogen can be easily injected into the combustor as a gaseous fuel to provide a uniform mixture of fuel and air prior to combustion, a more even distribution of flame temperature may be achieved to insure a low  $\text{NO}_x$  formation rate.

### Burning Velocity

The laminar burning velocities for hydrogen and a typical hydrocarbon (propane) are compared in figure 1 for a pressure of 1 atmosphere and for an initial ambient temperature. The maximum burning velocity for hydrogen is shown to be about 8 times greater than the maximum value for propane. The maximum burning velocity for hydrogen, unlike that for propane, does not occur near an equivalence ratio of unity, but instead occurs near a fuel-rich equivalence ratio of about 1.8.

The influence of pressure on burning velocity is not considered to be significant over the range of interest for

gas turbine combustors (ref. 11). Burning velocity increases exponentially with increases in initial temperature. The effect of turbulence on burning velocity is not well documented, however turbulent flames consume mixture more rapidly than laminar flames (ref. 9).

The higher burning velocity for hydrogen is attributed to a higher reaction rate and to higher mass diffusivity and thermal conductivity. From the viewpoint of combustor performance, the higher burning velocity for hydrogen enables stable combustion to occur at much more severe operating conditions (lower combustor inlet pressures and temperatures and/or higher velocities) than with JP fuel and introduces the possibility of completing combustion in a shorter length combustor. This is illustrated in figure 2, in which, the space heating rates are compared for hydrogen and JP-4 fuel. The combustion properties of JP-4, described herein, are similar to either JP-5 or commercial grade aircraft fuel (ASTM A-1). The space heating rate is indicative of the minimum combustor volume required to complete combustion at a given fuel flowrate or heat release rate. The shaded region on the curve represents the spread of experimental data for both turbojets and ramjets. The space heating rate limit shown for JP-4 is based on data from a perfectly stirred reactor experiment (ref. 12) in which fuel-air mixing is nearly instantaneous, and is approximately one order of magnitude higher than has been measured in practical gas turbine combustors which are limited by the rate of mixing. The limit shown for hydrogen was estimated from the ratio of the burning velocities for hydrogen and hydrocarbon fuels. The higher theoretical space heating rate for hydrogen suggests that a much shorter primary zone would be adequate for completing combustion. A shorter combustor is desirable from the viewpoint of reduced engine weight. Reductions in primary zone dwell time possible with hydrogen could result in a proportionate reduction in nitrogen oxide.

## NITROGEN OXIDE EMISSIONS

### Theoretical Calculations

The theoretical flame temperature is shown plotted against equivalence ratio for both hydrogen and JP fuel in figure 3. These data were obtained from the computer program of reference (13) for combustor inlet conditions (800 K, 5 atm) simulating supersonic cruise. The theoretical flame

temperature for both hydrogen and JP reaches a peak at an equivalence ratio of about 1.1. For these inlet conditions, the maximum flame temperatures for hydrogen and JP are 2640 K and 2560 K, respectively. The flame temperature for hydrogen is shown to be about 80 K greater than that for JP at identical conditions for values of equivalence ratio of 1 or less.

Nitrogen oxide formation may be minimized by maintaining the lowest flame temperature possible in the reaction zone. Because of the lean flammability limit, the minimum flame temperature for hydrogen is shown to be about 1100 K ( $\phi \approx 0.1$ ) compared to a value of about 1900 K ( $\phi = 0.5$ ) for JP fuel.

Theoretical chemical kinetics calculations were performed to determine formation rates for nitric oxide by using the computer program of reference (14). A premixed-prevaporized reaction was assumed. These computations were initiated by using the equilibrium compositions calculated from reference (13) for both hydrogen and JP at an inlet temperature and pressure of 800 K and 5 atmospheres, respectively. Since combustion reactions were assumed to occur instantaneously, the calculated equilibrium compositions were used as the initial reactant concentrations with the exception that the initial nitrogen oxide concentrations were set at zero. The nitric oxide producing reactions occurred at a constant reaction temperature equal to the equilibrium flame temperature for each given value of equivalence ratio. Since nitric oxide (NO) is the predominant oxide of nitrogen formed during combustion (substantially lesser amounts of nitrogen dioxide (NO<sub>2</sub>) are also formed), the theoretical results will be limited to this particular specie. A total of 7 intermediary kinetic reactions are considered in this computation, but the principal reactions forming nitric oxide are the so called Zeldovitch Reactions between (1) monatomic oxygen and diatomic nitrogen and (2) monatomic nitrogen and diatomic oxygen.

The results of these computations are presented in figure 4 for a reaction dwell time of 2 milliseconds, which is representative of combustor primary zones. Nitric oxide emissions are shown here in terms of a volumetric concentration. Equilibrium nitric oxide concentrations are provided for comparison with the values limited by chemical kinetics. The nitric oxide concentrations determined by kinetics are significantly lower than the equilibrium concentrations because of the relative slowness of the nitric oxide formation reactions. At identical conditions, the nitric oxide concentration shown for hydrogen is slightly higher than that for JP because of



the difference in flame temperature shown in figure 3. Figure 4 clearly shows the advantage of burning in the primary zone at as low an equivalence ratio as possible to minimize the formation of nitric oxide. Reductions might also be possible using a two-staged combustor by first burning fuel-rich and then burning the remaining fuel at a lean equivalence ratio after uniformly mixing in additional air.

The lowest nitric oxide concentration attainable by burning with a lean fuel-air mixture in the primary zone is determined by the lowest practical primary zone equivalence ratio. Emission characteristics of an experimental premixed-prevaporized propane burner were reported in reference (15). Results presented in reference (15) for an inlet temperature of 590 K indicate that combustion instabilities occurred for reaction zone equivalence ratios less than 0.54. To be conservative, a minimum primary zone equivalence ratio of 0.6 was assumed for JP fuel in order to insure stable combustion. For hydrogen, the minimum primary zone equivalence ratio is determined by the combustor over-all fuel-air ratio (combustor temperature rise) and the proportion of air required for combustor cooling. On this basis, a minimum primary zone equivalence ratio of 0.4 was arbitrarily selected for hydrogen. The results of these computations are shown in figure 5 in which nitric oxide concentration is plotted against dwell time for inlet conditions of 800 K and 5 atmospheres. The nitric oxide concentration using either hydrogen or JP fuel varies linearly with primary zone dwell time. For a primary zone dwell time of 2 milliseconds, the theoretical minimum nitric oxide concentrations are about 20 ppm for JP and 0.1 ppm for hydrogen. Within the limits of the theoretical model used to perform the theoretical computations, these results are only indicative of the ultimate minimum nitric oxide concentrations possible with either fuels. Practical combustor considerations such as the degree of mixing and uniformity of the reaction temperature may significantly increase these theoretical estimates. In any event, from a theoretical point of view, hydrogen has considerably more potential for minimizing the nitric oxide concentration than JP fuel because of its lower lean flammable limit, higher flame velocity and ability to produce a more uniform fuel-air mixture as a gaseous fuel.

### Experimental Test Data

Nitrogen oxide emissions were measured at the exhaust of an experimental turbojet combustor segment using gaseous

hydrogen fuel (ref. 16). The nitrogen oxide emissions obtained with hydrogen were compared with those obtained with both liquid ASTM A-1 (similar to JP5) and gaseous propane tested at similar combustor operating conditions. The experimental combustor used to obtain these data was not specifically designed as a low  $\text{NO}_x$  combustor; nevertheless, these data do indicate the trends and sensitivities of nitrogen oxide emissions with combustor operating conditions. The experimental combustor (figure 6) employed to obtain these data had been previously used to study the effects of prevaporized fuel on exhaust emissions (ref. 17). The combustor segment, which had a width of 0.31 m, a maximum height of 0.15 m and a length of 0.32 m, utilized 4 dual flow fuel injectors. Liquid ASTM A-1 fuel was injected through a simplex nozzle located in the center of the assembly, and either gaseous propane or gaseous hydrogen were injected through 8 evenly spaced orifices surrounding the simplex nozzle. Primary airflow passed through an inlet snout and entered the combustor through swirlers surrounding the fuel injectors. Secondary air entered the combustor through holes and scoops in the liner wall. Gas samples collected at the combustor exit were analyzed for total nitrogen oxides by a chemiluminescence meter and include both nitric oxide and nitrogen dioxide.

The effect of combustor inlet total temperature on nitrogen oxide concentrations for the three different fuels is shown in figure 7. The combustor temperature rise,  $\Delta T$ , was held constant at about 650 K. The inlet total pressure during the experimental tests was held constant at 4 atm. for hydrogen and at 10 atm. for both liquid ASTM A-1 and propane, but to provide a comparison for the fuels, the 10 atm. data were corrected analytically to values equivalent to 4 atm. by using a square root of pressure correction. The  $\text{NO}_x$  concentrations obtained with all three fuels increases markedly with increases in inlet temperature. The  $\text{NO}_x$  concentration levels for ASTM A-1 corrected to a pressure of 4 atmospheres were nearly identical to the  $\text{NO}_x$  concentration levels for hydrogen. From airflow distribution calculations, the primary zone equivalence ratios were estimated to be about 0.75 for ASTM A-1 and 0.43 for hydrogen. Based on the calculated primary zone equivalence ratio of 0.75 for ASTM A-1, the experimental results extrapolated to an inlet temperature of 800 K and inlet pressure of 5 atmospheres are of the same order of magnitude as the theoretical results presented in figure 4 for JP at the same value of  $\phi$  (correcting for the effect of dilution by the secondary air). On the other hand, the experimental  $\text{NO}_x$  results for hydrogen obtained at a calculated primary zone equivalence ratio of 0.43 are several orders of magnitude

higher than predicted from the theoretical results in figure 4. This large difference may be attributed to the fact that the experimental combustor was not optimized for minimum dwell time and that the fuel-air mixture was not completely mixed prior to combustion.

Several different primary zone equivalence ratios were tested with hydrogen by adjusting the primary zone airflow distribution. These results are shown in figure 8 as nitrogen oxide concentration plotted against flame temperature. The flame temperature was calculated for each primary zone equivalence ratio by assuming equilibrium conditions. The observed rate of reduction in  $\text{NO}_x$  with decreasing flame temperature is not as great as expected from theory (fig. 4). This may again be attributed to the fact that mixing uniformity was not optimized.

#### HYDROGEN COMBUSTOR TECHNOLOGY

Past experience established by the NASA Lewis Research Center in the design and development of gas turbine combustors for hydrogen fueled engines is described in references (2-7). Flight tests were conducted with a B-57 aircraft in which one of the production J-65 turbojet engines was modified to accept gaseous hydrogen as well as JP fuel. The modification to the J-65 combustor was relatively simple and merely involved a change to the inlet fuel manifold. Additional research was performed with the objective of generating short-length combustor designs to take advantage of hydrogen's unique combustion properties. One of the more promising short-length concepts investigated substituted a modular array of small-element combustors (swirl-cans) for the conventional full-annulus combustion chamber as shown schematically in figure 9. Figure 10 shows a quarter-sector test combustor that was used to simulate the performance of a full-annulus swirl-can combustor together with the details of each swirl-can combustor element. Hydrogen fuel was injected tangentially into the combustor element and mixed with primary air entering the upstream orifice. An array of small V-gutters surrounding each combustor element provided flame spreading and interfacial mixing with secondary air passing around each element. The swirl-can combustor has no well-defined primary or secondary zones as in the conventional combustor. Nearly all the airflow, except for that required to cool the liner, passes directly through or around each element. The combustor can be shortened because of the rapid burning and mixing that occurs downstream of each element. Figure 11 shows a

photograph of an experimental full-annulus swirl-can combustor that was tested in a J65 engine using hydrogen fuel (ref. 2). More recently, considerable research has been performed to adapt the swirl-can concept for JP fuel. Initially the reason for developing the JP swirl-can was to reduce engine weight by reducing combustor length, but lately interest has been stimulated by the potential for reducing nitrogen oxide emissions (ref. 8). Figure 12 shows a photograph of an experimental 120 module-full annulus JP swirl-can combustor.

### PREDICTED NITROGEN OXIDE EMISSIONS

Cruise operating conditions are presented in table I for both an advanced subsonic commercial aircraft (ATT, Advanced Technology Transport) and an advanced supersonic transport (ASST). These operating conditions are based on mission analyses presented in references (18 and 19).

The higher heating value of hydrogen relative to JP fuel is estimated to reduce both take-off gross weight and total engine airflow rate by 40 percent.

The subsonic mission assumes a payload of 300 passengers, and a range of 5560 kilometers. Take-off gross weight of the subsonic aircraft is about 170,000 kg using JP fuel and 101,000 kg using hydrogen. Three turbofan engines are specified for the subsonic mission. The engines selected resulted in a noise level of 91 EPNdb (16 EPNdb below the FAR 36 requirement). The bypass ratio during cruise is 4.2 using JP and 6.0 using hydrogen. The total fuel flow rate per engine during cruise is 2900 kg/hr using JP and 620 kg/hr using hydrogen (about 21 percent of the fuel flow rate using JP).

Four duct-burning turbofan engines were selected for the ASST mission to provide a minimum noise level of 108 EPNdb. A payload of 250 passengers and a range of 7400 km are assumed. Take-off gross weight for the ASST is about 382,000 kg using JP and 229,000 kg using hydrogen. The cruise bypass ratio is 2.36 using either JP or hydrogen. The combustor fuel flow rate per engine during cruise is 10,750 kg/hr using JP and 2560 kg/hr using hydrogen (about 24 percent of the fuel flow rate using JP). A small degree of augmentation is required during cruise that results in a duct-burner fuel flow rate of 4200 kg/hr of JP or 940 kg/hr of hydrogen (about 22 percent of the JP fuel flow rate). The total engine fuel flow rate during cruise is 14,950 kg/hr of JP or 3500 kg/hr of hydrogen (about 23 percent of the JP fuel flow rate).

Predicted nitrogen oxide emissions during cruise are presented in table II for both an ATT and ASST mission. Data for nitrogen oxide emissions are presented in terms of (1) the volumetric exhaust concentration (PPM), (2) an emission index in grams of  $\text{NO}_x$  per kilogram of fuel burned, and (3) an emission rate (kg of  $\text{NO}_x$  per hour per engine). The values shown for the emission rate are based on the cruise fuel flow rates presented in table I. The range of predicted  $\text{NO}_x$  emissions using JP fuel were calculated from reference (20) from a spread of  $\text{NO}_x$  emission data for both production engines and an experimental NASA swirl-can combustor. The data of reference (20) were adjusted to the operating conditions given in table I. The range of predicted  $\text{NO}_x$  emissions using hydrogen were calculated from the JP data presented herein by multiplying by the ratio of  $\text{NO}_x$  emissions for hydrogen to the  $\text{NO}_x$  emissions for JP presented in figure 8 and adjusting to the operating conditions given in table I.

The predicted  $\text{NO}_x$  exhaust concentrations (volumetric) for both the ATT and ASST combustors are of the same order of magnitude, and the hydrogen concentrations were slightly higher than those for JP fuel. The  $\text{NO}_x$  exhaust concentrations for the ASST augmentor (duct-burner) are only about 5 percent of the exhaust concentration from the core engine combustor with either JP or hydrogen. The predicted  $\text{NO}_x$  emission indices for the ATT and ASST combustors during cruise are at a similar level for a given fuel except that the emission indices for hydrogen are about three times greater than for JP. The hydrogen emission index is three times greater than the JP emission index mainly due to the difference in fuel-air ratio required for a given combustor temperature rise with either fuel (for a given temperature rise, the required JP fuel-air ratio is about 2.5 times greater than the required hydrogen fuel-air ratio) and the fact that emission index is inversely proportional to fuel-air ratio. The  $\text{NO}_x$  emission indices for the ASST augmentor for either JP or hydrogen are predicted to be about 30 percent of the corresponding values for the core engine combustor. For the ATT mission, the  $\text{NO}_x$  emission rate, kg  $\text{NO}_x$ /hr during cruise for hydrogen is calculated to be about two-thirds of the JP emission rate even though the emission index for hydrogen is three times greater than for JP. This is due to the fact that the hydrogen fuel flow rate is only about one-fifth of the JP fuel flow rate because of the combined effects of the higher heating value and reduced engine airflow rate (lower take-off gross weight) of hydrogen relative to JP. The total ASST  $\text{NO}_x$  emission rate (combustor plus augmentor) during cruise with hydrogen is calculated to be about 75 percent of the JP emission rate.

The ASST duct-burner has a  $\text{NO}_x$  emission rate that is about 12 percent of the value for the core engine.

These predictions are, of course, quite arbitrarily based on a range of  $\text{NO}_x$  emissions from available experimental data. The  $\text{NO}_x$  emission data obtained for hydrogen were obtained from an experimental combustor that was not specifically designed to minimize emissions with hydrogen fuel. Furthermore, the results from the analytical calculations presented herein indicate that a  $\text{NO}_x$  reduction of about 2 orders of magnitude better than obtained experimentally is theoretically possible. Experimental research will be required to determine the degree to which the lower theoretical  $\text{NO}_x$  emissions may be approached and to develop the technology for a low emission combustor using hydrogen.

#### CONCLUDING REMARKS

Considerably more potential exists for minimizing nitrogen oxide emissions with hydrogen than with kerosene because of its wide flammable limits and higher burning velocity, and because it may easily be introduced into the combustor as a gaseous fuel. Limited experimental data described herein show that the  $\text{NO}_x$  emission index,  $\text{g}(\text{NO}_2)/\text{kg fuel}$ , is about three times greater for hydrogen than for JP; however, if these results are applied to aircraft designed for a given mission, hydrogen's higher heating value enables the aircraft to have a lower gross weight and a lower fuel flow rate so that the  $\text{NO}_x$  emission rate,  $\text{kg}(\text{NO}_2)/\text{hr}$  may be reduced about 30 percent compared to JP. Theoretical kinetics calculations predict that much lower  $\text{NO}_x$  emissions are possible with hydrogen by lowering primary zone equivalence ratio and dwell time; however, combustor research is required to determine the practically achievable lower limits. Extensive research was performed in the mid-fifties at the NASA-Lewis Research Center to adapt the use of hydrogen fuel to gas turbine engines for high altitude aircraft. Much of the technology that is currently being evolved to reduce nitrogen oxide emissions in advanced combustors using JP may be adapted to the design of a low  $\text{NO}_x$  combustor for hydrogen. The "swirl-can" combustor or some other type of premixed combustor should be logical candidates for the design of a low  $\text{NO}_x$  hydrogen-fueled combustor.

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TABLE I.-CRUISE OPERATING CONDITIONS

	ATT		ASST	
	Mach number altitude 12 200 M	H <sub>2</sub>	Mach number altitude 19 800 M	H <sub>2</sub>
Total airflow rate, kg/sec	JP		JP	
Bypass ratio	190 4.2	115 6.0	336 2.36	202 2.36
Combustor airflow rate, kg/sec	37	16	100	61
Combustor inlet temperature, K	740	760	810	810
Combustor inlet pressure, atm.	10.1	10.7	4.7	4.7
Combustor exit temperature, K	1480	1670	1770	1770
Comb. fuel flow rate, kg/hr	2900	620	10 750	2560
Comb. fuel-air ratio	0.0220	0.0104	0.0299	0.01187
Bypass or duct-burner airflow rate, kg/sec	153	99	236	141
Augmentor inlet temperature, K	---	--	635	635
Augmentor inlet pressure, atm.	---	--	2.6	2.6
Augmentor exit temperature, K	---	--	835	835
Aug. fuel flow rate, kg/hr	---	--	4200	940
Aug. fuel-air ratio	---	--	0.00495	0.00187
TOTAL FUEL FLOW RATE, kg/hr	2900	620	14 950	3500

TABLE II.-PREDICTED NO<sub>x</sub> EMISSIONS DURING CRUISE

	ATT Mach number 0.98 altitude 12 200 M		ASST Mach number 2.7 altitude 19 800 M	
	JP	H <sub>2</sub>	JP	H <sub>2</sub>
Combustor				
NO <sub>x</sub> exhaust concentration, PPM	140-280	200-400	180-360	220-440
NO <sub>x</sub> emission index, g/kg fuel	10-20	30-60	10-20	30-60
NO <sub>x</sub> emission rate, kg/hr	30-60	20-40	110-220	80-160
Augmentor				
NO <sub>x</sub> exhaust concentration, PPM	-----	-----	10-20	10-20
NO <sub>x</sub> emission index, g/kg fuel	-----	-----	3-6	9-18
NO <sub>x</sub> emission rate, kg/hr	-----	-----	10-20	10-20
TOTAL NO <sub>x</sub> EMISSION RATE, kg/hr	30-60	20-40	120-240	90-180

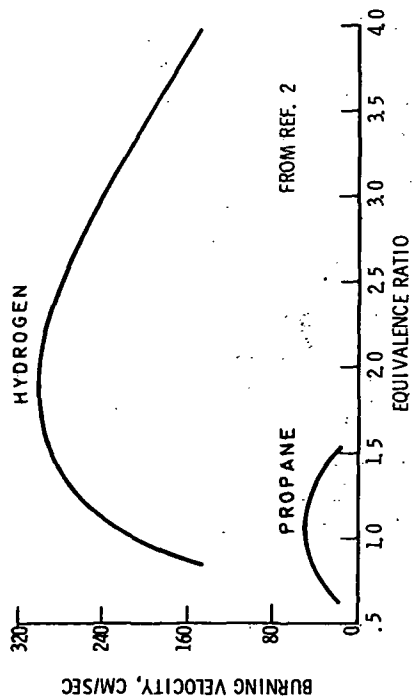


Figure 1. - Burning velocities for hydrogen and propane.

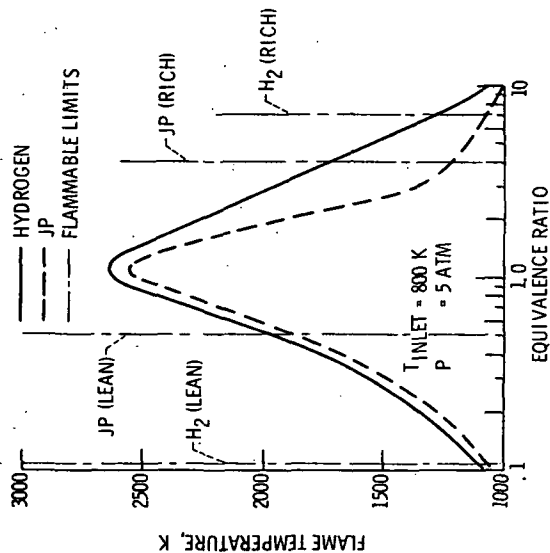


Figure 3. - Theoretical flame temperature.

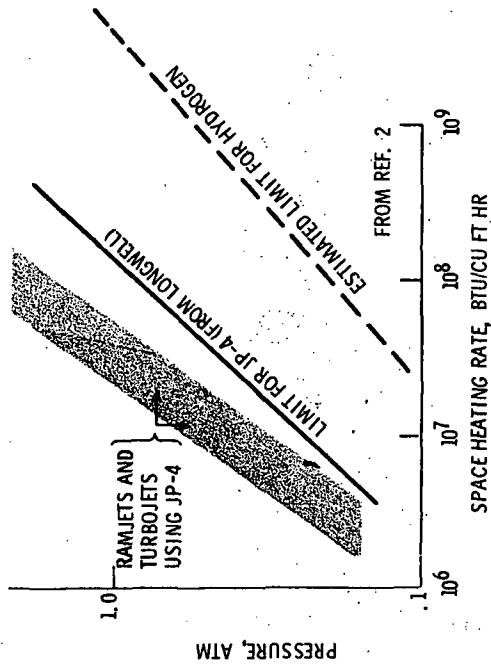


Figure 2. - Space heating rates for JP-4 and hydrogen.

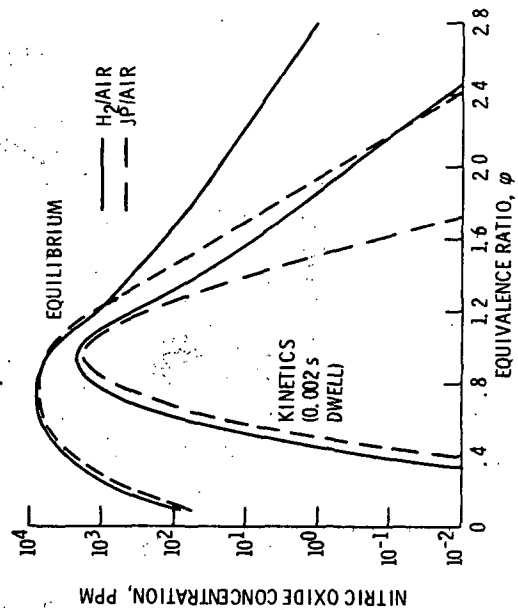


Figure 4. - Theoretical nitric oxide concentrations.  $T_3 = 800\text{ K}$ ;  $p_3 = 5\text{ atm}$ .

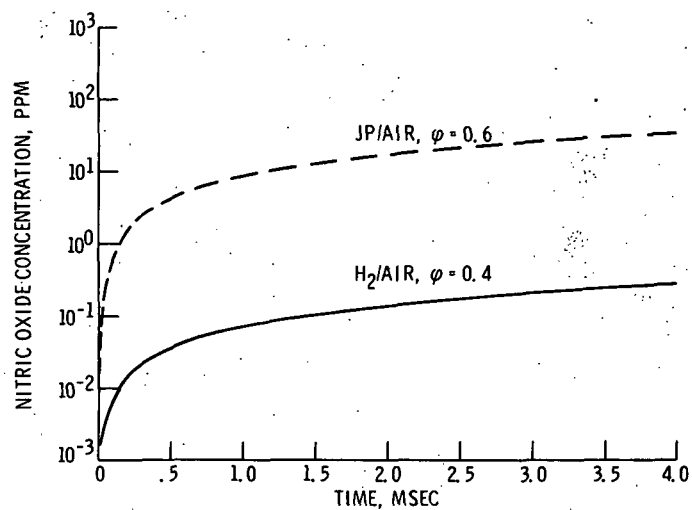


Figure 5. - Nitric oxide concentration for minimum primary zone equivalence ratio.  $T_3 = 800$  K;  $p_3 = 5$  atm.

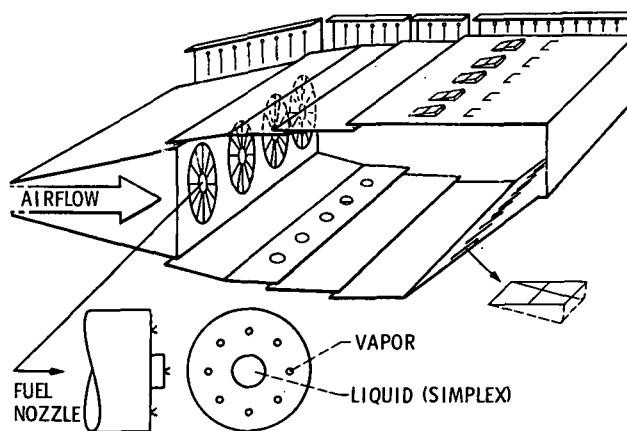


Figure 6. - Experimental vapor fuel combustor.

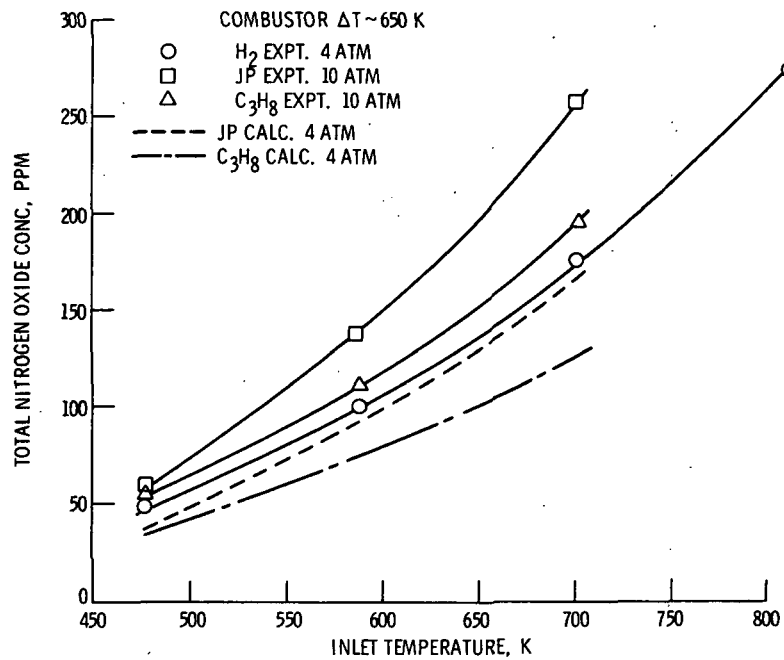


Figure 7. - Effect of inlet temperature on  $NO_x$  emissions from an experimental combustor.

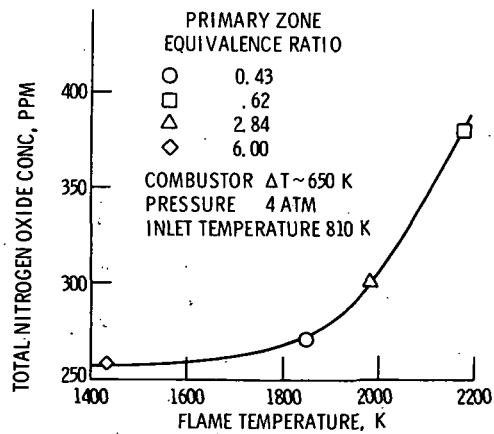


Figure 8. - Effect of flame temperature on  $NO_x$  emissions from an experimental combustor for hydrogen fuel.

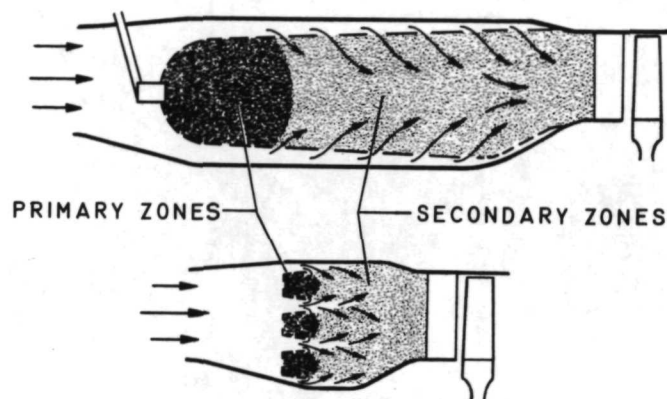


Figure 9. - Comparison of conventional combustor with small-element combustor.

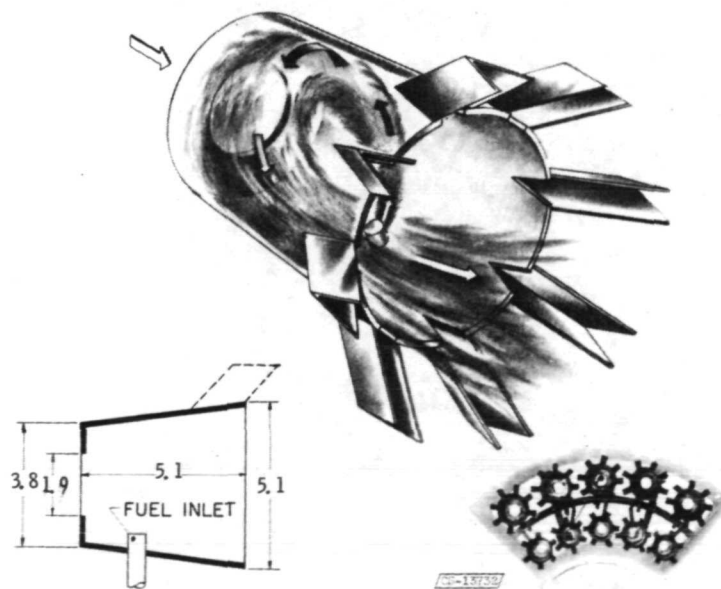
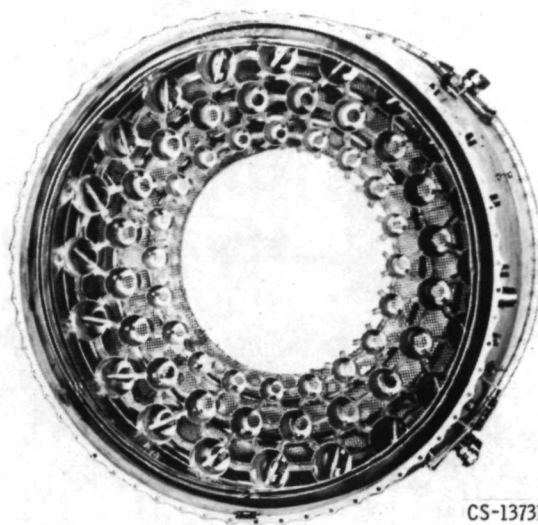


Figure 10. - Swirl-can combustor element. (Dimensions in cm.)



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Figure 11. - View of swirl-can combustor for hydrogen-fueled turbojet engine, looking upstream.

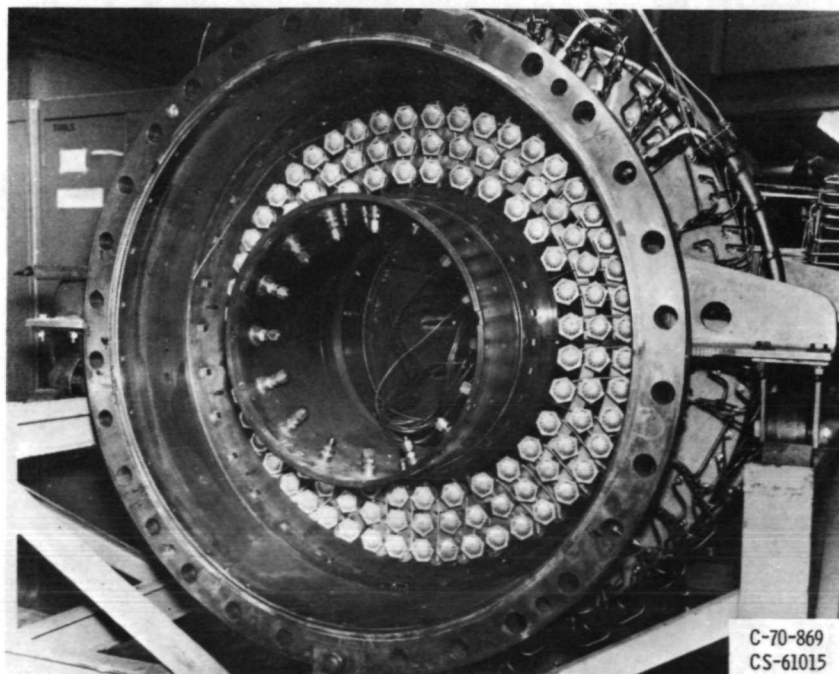
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Figure 12. - JP swirl-can combustor.